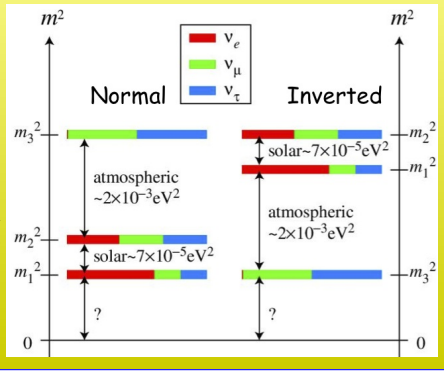
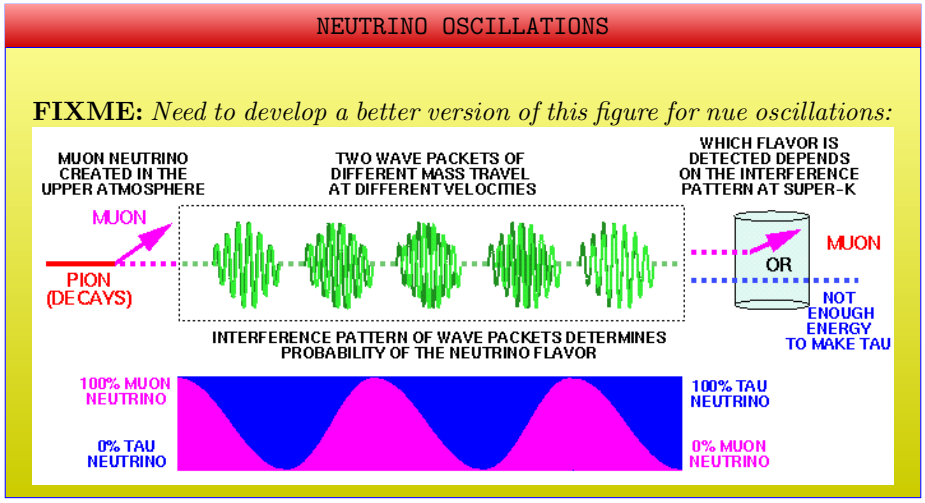
NEUTRINO MIXING

Neutrinos are weakly interacting elementary particles. There are three neutrino flavors which determine the lepton flavor (electron, muon, tau) produced in the weak charged current interaction of the neutrino. Neutrino flavors are not pure quantum eigenstates. Each neutrino flavor $(\nu_e, \nu_\mu, \nu_\tau)$ is an admixture of three quantum mass states (m_1, m_2, m_3) and vice-versa.



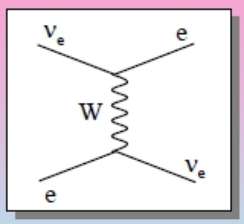

NEUTRINO OSCILLATIONS
FIXME: Need to develop a better version of this figure for nue oscillations:
MUON NEUTRINO CREATED IN THE UPPER ATMOSPHERE
TWO WAVE PACKETS OF DIFFERENT MASS TRAVEL AT DIFFERENT VELOCITIES
WHICH FLAVOR IS DETECTED DEPENDS ON THE INTERFERENCE PATTERN AT SUPER-K
MUON
PION (DECAYS)
OR
MUON
NOT ENOUGH ENERGY TO MAKE TAU
INTERFERENCE PATTERN OF WAVE PACKETS DETERMINES PROBABILITY OF THE NEUTRINO FLAVOR
100% MUON NEUTRINO
0% TAU NEUTRINO
100% TAU NEUTRINO
0% MUON NEUTRINO

THE MATTER EFFECT

FIXME: *From a presentation by Smirnov - need to redo for GeV ν*

L. Wolfenstein, 1978

Elastic forward scattering → Potentials V_e, V_μ



- $V \sim 10^{-13}$ eV inside the Earth for E = 10 MeV
- Difference of potentials is important → for ν_e ν_μ:

$$V_e - V_\mu = \sqrt{2}\, G_F n_e$$

- Refraction index:

$$n - 1 = V / p$$

- Refraction length:

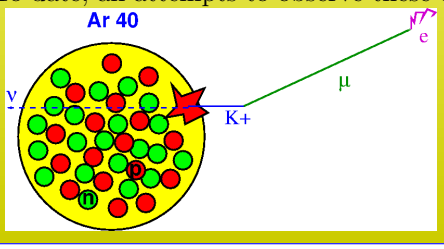
$$l_0 = 2\pi / (V_e - V_\mu) = \sqrt{2}\,\pi / G_F n_e$$

- $n - 1 \begin{cases} \sim 10^{-20} & \text{inside the Earth} \\ < 10^{-18} & \text{inside the Sun} \\ \sim 10^{-6} & \text{inside the neutron star} \end{cases}$

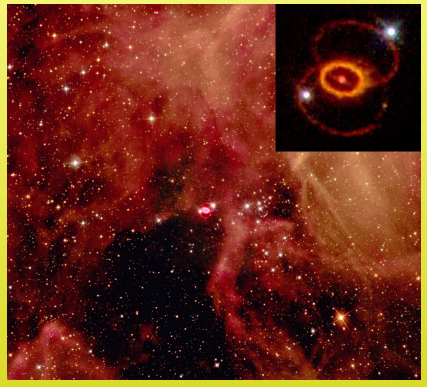
- Neutrino optics → focusing of neutrinos fluxes by stars, complete internal reflection, etc

PROTON DECAY

FIXME: *text taken verbatim from Wikipedia:*
In the Standard Model, protons, are theoretically stable because baryon number (quark number) is conserved. Therefore, protons will not decay into other particles on their own, because they are the lightest (and therefore least energetic) baryon. Some beyond-the-Standard Model grand unified theories (GUTs) explicitly break the baryon number symmetry, allowing protons to decay via the Higgs particle, magnetic monopoles or new X bosons. Proton decay is one of the few observable effects of the various proposed GUTs. To date, all attempts to observe these events have failed.



SUPERNOVA BURST NEUTRINOS



1987A supernova remnant near the center. Composite of two public domain NASA images taken from the Hubble Space Telescope.

FIXME: *taken verbatim from Wikipedia* In 1966 Colgate and White calculated that neutrinos carry away most of the gravitational energy released by the collapse of massive stars, events now categorized as Type Ib and Ic and Type II supernovae. When such stars collapse, matter densities at the core becomes so high (1017 kg/m3) that the degeneracy of electrons is not enough to prevent protons and electrons from combining to form a neutron and an electron neutrino. A second and more important neutrino source is the thermal energy (100 billion kelvins) of the newly formed neutron core, which is dissipated via the formation of neutrino-antineutrino pairs of all flavors.